

University of Dundee

Reconstruction and paleoclimatic significance of late Quaternary glaciers in the Tararua Range, North Island, New Zealand

Brook, Martin S.; Kirkbride, Martin P.

Published in:
Quaternary International

DOI:
[10.1016/j.quaint.2017.10.018](https://doi.org/10.1016/j.quaint.2017.10.018)

Publication date:
2018

Licence:
CC BY-NC-ND

Document Version
Peer reviewed version

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):

Brook, M. S., & Kirkbride, M. P. (2018). Reconstruction and paleoclimatic significance of late Quaternary glaciers in the Tararua Range, North Island, New Zealand. *Quaternary International*, 470(Part A), 53-66.
<https://doi.org/10.1016/j.quaint.2017.10.018>

General rights

Copyright and moral rights for the publications made accessible in Discovery Research Portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from Discovery Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain.
- You may freely distribute the URL identifying the publication in the public portal.

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Reconstruction and paleoclimatic significance of late Quaternary glaciers in the Tararua Range, North Island, New Zealand

Martin S. Brook^{a,*}

Martin P. Kirkbride^b

^aSchool of Environment, The University of Auckland, Auckland 1142, New Zealand

^bGeography, School of Social Sciences, University of Dundee, Dundee DD1 4HN, UK

**Corresponding author. Email address: m.brook@auckland.ac.nz (M.S. Brook).*

© <2017>. This manuscript version is made available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

ABSTRACT

Reconstructed mountain glaciers are routinely used as a proxy for climate in the search for evidence of interhemispheric climate fluctuations during the Quaternary. In New Zealand, valley glaciers at the Last Glacial Maximum (LGM) extended from an ice sheet centred on New Zealand's Southern Alps to below present-day sea level. In contrast, evidence of LGM glacial activity on the North Island is rare. Here, a glacioclimatic reconstruction is presented of two former glaciers in the Tararua Range (41°S) in the southern North Island. At Mt. Aston, an isolated cirque basin contains landform evidence of a marginal niche glacier. At Park Valley, the lateral moraine of a larger cirque glacier has yielded published cosmogenic isotope ages. The paleoglacier reconstruction shows that paleoequilibrium line altitudes increased northwards across New Zealand during the local LGM. Hence, at this latitude only topography >1200 m above present day sea-level was of sufficient elevation to allow small glaciers to form. The Mt Aston glacier covered only 0.18 km² with an equilibrium line altitude (ELA) of *c.* 1287 m above present sea level. A mean ELA glacier thickness of *c.* 25 m gives a basal shear stress at the ELA of *c.* 100 kPa⁻¹, with a mean summer (December, January, February, DJF) temperature at the ELA of no lower than 5.5°C below present, below which precipitation would have been insufficient to support the reconstructed glacier. Implied LGM paleo-temperatures from both the ELA reconstruction and the glaciological reconstruction broadly accord with other paleo-temperature proxies from the North Island. Park Valley glacier covered *c.* 0.45 km² with an ELA of *c.* 1270 m and a mean ELA basal shear stress of 65 kPa. Its balance discharge was 9× greater than at Mt Aston. It appears to have been glaciologically viable across a wide range of paleotemperatures: thus, the more marginal glacier is a more useful paleoclimatic indicator because it places a maximum limit on LGM temperature depression, which the larger glacier does not. ELAs of both glaciers closely approximate the regional LGM ELA trend surface. The paleo-glacier reconstructions imply that together with temperature driving LGM paleo-ELA depression, changes in south-westerly airflow over New Zealand, bringing moisture-laden but cool air, maximized snowfall and minimised winter melt. The corollary is that patterns of Quaternary glacier fluctuations may be interpreted as responses, at least in-part, to precipitation-driven changes, and secondly, North Island glaciation was probably more extensive than previously assumed.

Keywords:

Niche glaciation; Southern mid-latitudes; Glacier reconstruction; Tararua Range; New Zealand

1. Introduction

Explaining the growth and decay of glaciers during the late Quaternary in the Southern Hemisphere remains an unresolved question, especially during the last glacial cycle. New Zealand is one of the few locations in the Southern Hemisphere where a range of paleoclimatic records are available, and a range of proxy records indicate that climate was influenced by the interaction of oceanic, cryospheric and atmospheric factors (Barrell et al., 2013). The strong topographic and climatic control on glacial activity on both the South and North Islands currently allows glaciers to form between 39° to 46° S latitude (Purdie et al., 2014; Eaves et al., 2016a). Geological evidence has often been used to record and infer the distribution of former glaciation during the (*c.* 30-18 ka) New Zealand “Last Glacial Cold Period” (LGCP; Barrell et al., 2013), which coincides with the global Last Glacial Maximum (LGM). Along with other proxy records, this has led to marked spatial differences in terrestrial LGM temperature reconstructions, from +0.5 to –9°C (summarised in McKinnon et al., 2012). Much of this work is limited to the South Island, where large valley glaciers extended out from a small ice sheet formed along the axis of the Southern Alps (Porter, 1975; Doughty et al., 2013; Putnam et al., 2013). In contrast, on the North Island, terrestrial evidence for former glaciation is much less obvious, and appears to have been limited to volcanoes (Mathews, 1967; McArthur and Shepherd, 1990; Eaves et al., 2016b) and the Tararua Range on the southern North Island (Brook and Brock, 2005; Brook et al., 2005; Brook and Crow, 2008; Brook et al., 2008; Brook, 2009). Indeed, while quantitative reconstructions of paleoclimate (namely temperature and precipitation) during the LGM based on glacier fluctuations have shown some consistency across the South Island, independent estimates of paleoclimatic variables based on evidence from North Island glaciers are extremely rare (Brook et al., 2008; Eaves et al., 2016a,b). While the equilibrium line altitude (ELA) reconstructions and paleoclimate modelling from Eaves et al. (2016b), is a valuable additional dataset, effects of effusive volcanism and post-glacial flank collapse on the North island volcanoes hamper the delineation of glacial-geomorphic landforms, making ELA reconstructions problematic (Donoghue et al., 1997).

The forcing factors behind southern mid-latitude glaciation during the last glacial cycle are ambiguous, with insolation appearing to not be the sole factor controlling Southern Hemisphere climate change (Doughty et al., 2015). Indeed, recent work (Darvill et al., 2016) has highlighted that glacier expansion was broadly synchronous between New Zealand and Patagonia, and that climate forcing was related to an equatorward shift in the moisture-bearing south-westerly winds and oceanic fronts. Within New Zealand, the topography, maritime mid-latitude position and high precipitation gradients across the landmass mean that glaciers are highly sensitive to climate changes. Indeed, current glaciers in the Southern Alps, are particularly sensitive to climate change with estimates of the mass balance sensitivity at between 1.3-2.0 m w.e K⁻¹ (Anderson et al., 2010). High annual precipitation rates in some catchments of >12 m a⁻¹ leads to mass balance response at the termini of some valley glaciers of less than a decade (Purdie et al., 2014). Nevertheless, current ELAs across the Southern Alps vary markedly, from around 1500 m in the south and west, to 2500 m in the east in the Kaikoura Range (Lamont et al., 1999; Bacon et al., 2001). Moreover, on the North Island, current ELAs on Mt Ruapehu are much higher, close to the summit altitude (2797 m; Brook et al., 2011). Thus, large spatial variabilities in current ELAs occur, with paleo-ELAs depressed by *c.* 1000 m, thought to indicate *c.* 6-6.5 °C of temperature depression, although the effects of precipitation on mass balance and ELA depressions remain debatable (Shulmeister et al., 2004, 2010). Hence, resolving the magnitude of late Quaternary glacier fluctuations outside of the Southern Alps, and identifying other established formerly glaciated sites on the North Island will provide insights into the prevailing climatic gradients during the LGM.

Here, we report evidence of two cirque glaciers in the southern Tararua Range (40°55'S, 175°18' E). Below the summit of Aston (1376 m a.s.l.) a shallow cirque basin lies ~25 km south of established former glacial sites further north in the Tararua Range (Brook and Brock, 2005; Brook et al., 2005; Brook et al., 2008; Brook, 2009). Among the latter, the well-documented Park Valley moraine forms the basis for a second glacier-climate reconstruction. The aims of this research are to: (1) present geomorphological evidence supporting late Quaternary glaciation of the Mt Aston

basin; (2) reconstruct the glaciological and paleoclimatic environments that would have led to glaciation of the Aston and Park Valley cirques; (3) examine paleoclimatic implications of glaciation during the LGM in the southern North Island of New Zealand.

2. Study Area

The currently glacier-free Tararua Range is part of the axial ranges of the North Island, which are oriented north-south along the Australian-Pacific convergent plate margin (Stratford and Stern, 2006). The Tararua Range is a relatively young, deeply entrenched mountain range, a result of major faulting and folding, and in some places still active uplift (Nicol and Beavan, 2003). Bedrock is composed of quartzo-feldspathic metasediments of the Torlesse Terrane (Begg and Johnston, 2000). The Tararua Range summit altitudes are much lower (*c.* 1500 m a.s.l.) and northward of the Southern Alps, so late Quaternary glaciation was much more restricted, with only six cirque and valley glacier sites previously mapped (Adkin, 1911; Brook and Brock, 2005). Cosmogenic radionuclide exposure (CRNE) ages of the timing of glaciation in Park Valley (Figure 1) indicate that glaciation in the Tararua Range terminated around 18 ka (Brook et al., 2008), coinciding with the global LGM. This termination also accords with the synthesis of late Quaternary New Zealand paleoclimate of Alloway et al. (2007), as well as the recent CRNE ages of moraine boulders from Mt Ruapehu in the central North Island (Eaves et al., 2016a).

The Tararua Range (Figure 1, 2) is one of the wettest locations in New Zealand, with mean annual precipitation (1972-2013) exceeding 4000 mm a⁻¹ (Chappell, 2014). Mean annual temperatures at Kaitoke (223 m a.s.l.), 15 km to the southwest of the Aston basin are 15.3°C (Chappell, 2014). The Aston basin (40°58'13.15"S, 175°15'52.49"E) is the only valley head in the immediate vicinity with the glacial characteristics of a cirque (Evans and Cox, 1995; Barr and Spagnolo, 2015). It forms a bowl-shaped hollow, with exposed bedrock, perched above an upper tributary of the Tauherenikau River (Figure 2). The basin lies to the east below the Dress Circle ridgeline (Figure 3), which is part of the Southern Crossing hiking route across the Tararua Range.

The basin is bounded to the south by the Aston summit (1376 m), with the backwall and sides vegetated by tussock.

Park Valley (40°45'0.29"S, 175°25'44.65"E) is an impressive southwest-facing valley (Figure 4, 5), U-shaped in its uppermost section (Brook et al., 2005), indicative of glacial erosion. The adjacent summits surrounding the valley head rise to *c.* 1500 m. The head of Park Valley is composed of two cirque-like basins, feeding into the larger U-shaped valley, with a lateral moraine formed on the true right of the valley at the lip of the westernmost cirque. The distal end of the moraine is truncated by erosion, and ends *c.* 70 m above the valley floor. This is the only established moraine in the Tararua Range (Brook and Crow, 2008), and allows accurate constraining of the former extent of the Park Valley glacier. Hence, the Park Valley paleoglacier extent is used here as a comparison with the Mt Aston cirque climate reconstructions.

3. Methods

3.1 Geomorphology

Geomorphological mapping of the basin and surrounding slopes was undertaken using an enlarged 1:50,000 Land Information New Zealand (LINZ) topographic base map ("TOPO 50") overlain on a LINZ aerial image at a scale of 1:5,000, using established methods (Harrison et al., 2015).

Landforms and landform assemblages mapped include in situ rock, moraine ridges, slope failure scarps, and small debris flows from mobilisation of weathered soils (Figure 3, 5). Interpretation was also focused on identifying features of deglaciation such as meltwater channels.

3.2 Glacier, paleo-ELA reconstruction and potential snow blow areas

The reconstruction of the surface area of the Aston cirque glacier and the Park Valley glacier was based on the existing topography and geomorphology. The paleo-equilibrium line altitude (ELA) and snow blow allow the approximation of paleoclimate in terms of precipitation and temperature (Carr et al., 2010). The glacier reconstructions were used to estimate the former ice surface

topography, volume, thickness, basal shear stress and velocity. Reconstructing the glacier followed a sequence outlined in detail in Kirkbride et al. (2015). Initially, the glacier outline was superimposed on the base map and aerial image in ArcGIS 10.3, and the glacier surface was contoured at 20 m intervals. An indicative flow-line map was then produced with flowlines crossing each contour perpendicularly. Ice thickness was reconstructed by sampling the depths between interpolated ice surface and subglacial contours from the LINZ Topomap. Cirque floor sediment was ignored, which causes a very minor thickness underestimate toward the terminus, tapering to zero at the lateral and up-glacier margins. For surface slope and basal shear stress, a 100 m sampling grid was used, and the individual measurements were then interpolated in Surfer 12 software. Basal shear stress was calculated using the formula:

$$\tau_b = \rho g h \sin \alpha, \quad (1)$$

where ρ is ice density (0.9 t m^{-3}), g is the gravitational constant (9.8 m s^{-2}), h is ice thickness (m), and α is surface slope in degrees. A shape factor (0.7) was added to calculate the values of τ_b , following Weertman (1971). The paleo-ELA was calculated using the accumulation area ratio (AAR) method of Nesje and Dahl (2000), applying an AAR value of 0.6 ± 0.05 , which is deemed appropriate by Nesje and Dahl (2000) for cirque glaciers.

Often, small glaciers can have mass deficiencies when paleo-ELAs are calculated using standard techniques, and local topoclimatic factors are then invoked to contribute additional mass to sustain the former glacier (Plummer and Phillips, 2003), outside of conditions governed by regional climate envelopes (Carr and Coleman, 2007). In particular, the potential effects of snow blow on accumulation followed the approaches of Mitchell (1996), whereby the surrounding terrain that potentially contributed snow blow is identified. This assumes that all ground lying adjacent to, or above the calculated paleo-ELA had the potential to contribute snow blow. Not all areas above the paleo-ELA have an equal chance of contributing to accumulation, particularly with increased distance from the paleo-glacier. A snow blow factor was also calculated, following Sissons (1980).

This is the square root of the ratio of glacier area to potential snow blow area. Following Mitchell (1996), potential snow blow area and snow blow factor are plotted on a polar plot using 15° bins.

3.3 *Reconstruction of ELA, ablation gradient, mass flux and ice velocity*

The present-day summer (T_3 , here December to February) freezing levels in the Tararua Range can be calculated based on present-day temperature data from five National Institute of Water and Atmospheric Research (NIWA; <https://cliflo.niwa.co.nz/>) meteorological stations, and this data was then contoured. Climatic and glaciological conditions were estimated at the reconstructed steady-state ELAs (e.g. Brook and Crow, 2008) using the method of Carr et al. (2010). The method is based on Ohmura et al.'s (1992) global relationship between mean annual ELA precipitation (P_a) and temperature of the warmest three months in the year (T_3 , December to February):

$$P_a = 645 + 296T_3 + 9T_3^2 \quad (2)$$

where P_a indicates total accumulation at the ELA (in mm a⁻¹ water equivalent), and T_3 is the 3 month mean summer (December-February in °C for the Southern Hemisphere) temperature at the ELA. This defines the total accumulation and summer precipitation envelope required to sustain a glacier for a given ablation season temperature, incorporating all atmospheric precipitation, as well as snow blow and avalanching (Carr et al., 2010). The derived total accumulation can then be used to determine an indicative ablation gradient (a_z), in mm⁻¹ water equivalent) of the glacier, using the empirical relationship derived from modern glaciers, whereby:

$$a_z = 0.000781P_{a2} - 0.000568P_a + 3.33. \quad (3)$$

From this, the ablation gradient is used to determine net ablation within each 20 m contour range.

As the reconstructed glacier is assumed to be in steady-state conditions, the reconstructed total net ablation also equates to net accumulation above the ELA, using an ice density of 0.91 kg m³.

Application of the method in other studies has usually taken an independent value of T_3 , usually derived from palaeoecological studies, as a basis for estimating paleo-precipitation (e.g. Benn and Ballantyne, 2005; Finlayson et al., 2011; Kirkbride et al., 2014, 2015). While independent estimates

of paleo-temperature are available for the North Island (McLea, 1990; Shulmeister et al., 2001; McGlone and Topping, 1983; Eaves et al., 2016a), we adopt a different approach in which the paleoclimate modelling is run for a range of summer temperatures to test the viability of the resulting glaciological reconstructions. By this process, it is possible to discover the maximum possible LGM temperature depression at which marginal glaciation could have existed.

Reconstructed LGM temperature depressions for New Zealand range from almost zero to 9° cooler than present (McKinnon et al., 2012), with larger differences from present in and around the South Island. We adopt a range of summer temperature differences from -1° to -9° , and for each T_3 value we calculate P_a and a_z . Applying a_z to the glacier hypsometry derives annual mass loss which equates to the ice flux through the ELA cross-section for a glacier in equilibrium balance, and provides the balance velocity. The width-averaged creep velocity through the ELA is derived independently from the flow law, and the difference between the balance and creep velocities is the sliding velocity (Carr et al., 2010). Given that sliding velocity must be positive, a limit of viability is reached when colder temperatures, associated with lower precipitation, reach a threshold value at which the glacier accumulation zone is no longer providing sufficient mass to sustain the ice flux due to creep alone through the ELA. At colder temperatures, a negative sliding velocity is calculated. Unlike previous studies, no unique combination of summer temperature and annual accumulation is given here. Instead, the climatic limit of glacier viability that we identify is compared to the published range of temperatures and a convergence of different proxy estimates is sought. It is emphasised that this approach is possible only where a reconstructed glacier existed very close to the climatic limit of glaciation. Most published reconstructions of Lateglacial glaciers yield ELA ice fluxes associated with a wide range of temperature/precipitation combinations (Carr et al., 2010).

4. Results

4.1 Geomorphology

The Aston basin is oriented south-east and displays several characteristics of ‘classic’ cirques, but is lacking in some attributes. Morphometric evidence suggesting significant glacial erosion of the basin includes the steepened backwall and enclosed basin-shape. Indeed, it is circular to oval in planform, is around 650-700 m in length, and has a maximum width of *c.* 550 m (Figure 3). The basin has an over-deepened floor compared with neighbouring valley heads. Indeed, neighbouring valley heads are typically narrow, with convex-upward slopes indicative of fluvial incision, and are free of debris ridges. In contrast to these neighbouring valley heads, the rounded morphology of the Aston basin suggests glacial erosion, although the back wall is rounded and concave, lacking the high relief headwall present at many alpine cirques in the Southern Alps. Indeed, steeper slopes with rock exposures are most prevalent on the north-eastern side of the basin. An arcuate scarp marks a recent shallow failure, and any supraglacial debris accumulations would have been by frequent small rock falls from rock knobs, rather than high-magnitude events.

The floor of the basin is covered by 5 m of unconsolidated sediments and with a complex surface arrangement of low (<5 m) ridges, interpreted as moraines, and meltwater channels. The present stream, a tributary of the Tauherenikau River, drains the basin and is incised into the sediment-covered cirque floor. The sediment on the basin floor is discontinuous, with several low, lobate to arcuate ridges visible on the floor of the basin toward the former glacier terminus. These are marked by elongated morainic mounds, which are formed on gently-sloping ground, covered in grassy tussock, likely to be remnants of originally larger features that have been degraded by the high annual rainfall (>4000 mm a⁻¹) since deposition (<18 ka) during the LCGP. Small undulations in the sediment-covered basin floor also suggest meltwater incision into the moraine during deglaciation. The moraines are poorly defined, but are traceable to an elevation of about 1260 m a.s.l. The slopes around the glacier would not have been steep enough for large volumes of supraglacially-sourced rockfall debris to be deposited on the glacier surface, explaining the lack of a large terminal moraine. The geomorphology of the site indicates that the Aston cirque is a ‘simple’ cirque using the

classification of Benn and Evans (2010), in that it is a distinct, independent basin, and a ‘grade 4’ cirque on the basis of the Evans and Cox (1995) classification scheme.

In contrast, the Park valley site (Figure 4, 5) represents classical landforms of glacial erosion and deposition, including cirque basins, a U-shaped valley floor, and a lateral moraine. The two cirque basins at the head of Park Valley are grade 1 ‘classic’ cirques according to the Evans and Cox (1995) classification scheme, and are perched above the valley floor, with their thresholds incised by postglacial fluvial incision. Brook et al. (2008) report cosmogenic ^{10}Be moraine and bedrock exposure ages of *c.* 18 ka in Park Valley. Brook (2009) later identified the Kawakawa Tephra within the Park Valley moraine, which suggests the valley represents a composite glacial landsystem, first occupied prior to 25.4 ka (Brook and Crow, 2008).

4.2 *Glacier reconstruction and paleoclimatic implications*

Reconstruction of the former equilibrium line altitude (ELA) of a small glacier such as the Aston cirque glacier is problematic, as lateral moraines are absent. The reconstructed ELA in Figure 6 is at 1287 m, and this is based on an AAR of 0.6 from the reconstructed hypsometry (Figure 6). A reconstruction of Park Valley glacier is also included in Figure 6 for comparison, and its reconstructed ELA based purely on an AAR of 0.6 is 1220 m. The surface of the reconstructed Aston cirque glacier was of rather uniform gradient, with a maximum of *c.* 25° in a narrow zone toward the terminus. It then grades into a low angle lobe. Glacier hypsometry shows a modal elevation above 1250 m, reflecting the broad accumulation basin above the ELA (Figure 7). As ninety percent of the glacier area was between 1200 and 1350 m a.s.l. elevation, the glacier AAR would have been very sensitive to ELA fluctuations across this interval. From the Aston cirque glacier reconstruction (Figure 7A-D), reconstructed glacier thickness allows the calculation of basal shear stress, with maximum values of *c.* 125 kPa under a combination of steep surface and substantial thickness (>40 m), but typically of the order of *c.* 100 kPa at the centre of the ELA. From the Park Valley glacier reconstruction (Figure 7E-H), maximum surface slope was steeper,

though mean basal shear stress around the ELA was *c.* 75 kPa. Table 1 presents a summary of the reconstructed glaciological parameters for the full range of summer temperature scenarios for the two glaciers.

Using the lateral moraine at Park Valley, reported in Brook and Crow (2008), this allows the ELA to be calculated using the maximum elevation of lateral moraine (MELM) method (Benn and Evans, 2010) to be calculated. Using this, an ELA for the former Park Valley glacier of 1260 m a.s.l. is estimated. Altitudinal freezing levels from the current DJA temperature record (Figure 8) and precipitation can be used to reconstruct glaciological parameters reported in Figure 9 for both the Aston cirque glacier and the Park Valley glacier. The Park Valley glacier had an area *c.* $2.4 \times$ that of Aston glacier, and a balance flux of *c.* $9 \times$ times greater (Figure 9, Table 1). Under all climate scenarios, at least 90% of the ELA flux would have been by basal sliding, and thus the Park Valley glacier lay well within the envelope of climatic viability. In contrast, the small (18 ha) Aston cirque glacier could only have existed if ELA summer temperature exceeded 3.2°C, equivalent to an LGM temperature depression of at most 5.5°C (Figure 9). At lower summer temperatures, modelled accumulation values are below the balance fluxes necessary to sustain a glacier of the dimensions reconstructed from the geomorphological evidence. Results from Aston cirque glacier therefore also places a lower summer ELA temperature limit on the Park Valley glacier, because the two sites are distant by only 27 km. Indeed, a maximum possible temperature depression of 5.5°C (equivalent to an LGM DJA temperature of 3.2°C at the ELA) is associated with a sliding velocity of *c.* 10 m yr⁻¹, or *c.* 93% of ice motion (Figure 9, Table 1).

Finally, the potential effects of geomorphology on controlling snow blow, and so the viability of the Aston cirque glacier can be tested by comparing the area of land surface lying above the ELA of the reconstructed glacier (Figure 10A, Table 2). This shows a pronounced concentration of land surface above the ELA to the northeast of the former glacier, between 30° and 60° (Figure 10B), and this is again emphasised by the snow blow factors (Figure 10C, Table 2). Nevertheless, as dominant wind directions are from the west and south-west, the effective contribution of snow blow

to overall accumulation is likely to have been limited. No enhancement of accumulation by blown snow is therefore factored in to the glacioclimatic reconstruction. A similar snow blow effect probably occurred at Park Valley (Figure 11, Table 3), with most of the topography above the ELA being narrow ridgelines to the northeast, in the lee of the glacier accumulation zone, given prevailing wind directions. Hence, snow blow is also unlikely to have had a significant effect on accumulation at the Park Valley paleoglacier.

5. Discussion

The Aston cirque glacier appears to be the only site in the southern Tararua Range where glacial ice developed during the LGM. While glaciers developed in close proximity to the >1500 m elevation peaks in the centre of the range *c.* 25 km to the north, elsewhere, cold climate landforms formed during the LGM hitherto appeared to have been limited to periglacial activity (Brook and Williams, 2013). Further south in the Tararua Range towards Wellington, solifluction lobes and ice wedge features were identified by Cotton and Te Punga (1955), which ¹⁴C dating suggests date to the LGM (Augustinus, 2002). Thus, the Aston cirque glacier is a significant site, as it provides direct evidence of the southern-most extent of LGM glaciation on the North Island of New Zealand. Moreover, it appears to place a stringent limit on the North Island temperature depression at LGM, which helps to reconcile the wide range of values derived from different climate proxies (Seltzer et al., 2015). Indeed, it is the only glaciological reconstruction for central New Zealand to date.

The glaciological model predicts a maximum viable LGM temperature depression at the Aston cirque (5.5°C), and this accords closely with the 5.6°C LGM temperature reduction recently modelled for the Mangatepopo valley on the Tongariro massif in the central North Island (Eaves et al., 2016a). The estimate by Eaves et al. (2016a) accords with McGlone and Topping's (1983) LGM cooling of 4.6-5.9°C from close to Mt Ruapehu, and also assumes precipitation during the LGM was similar to the present day. There is a lack of quantitative LGM precipitation estimates in New Zealand, but proxy reconstructions and models typically indicate that annual precipitation was

similar or slightly lower than present (Drost et al., 2007; Whittaker et al., 2011; Golledge et al., 2012). This is an important consideration, because the suggested reduced annual precipitation on the North Island would require increased atmospheric cooling to reconcile the reconstructed ELA. Modelled LGM temperature depressions in the Southern Alps are of the order of *c.* 6-7°C compared with the present (Golledge et al., 2012; McKinnon et al., 2012), while offshore estimates are of the order of *c.* 4-7°C (Pahnke and Sachs, 2006). However, other North Island LGM temperature proxies are lower, and consistent with the Eaves et al. (2016a) reconstruction, and the implied maximum temperature depression from the Aston cirque. Indeed, dissolved noble gases in groundwater indicate a 4-5°C cooling (Seltzer et al., 2015), while fossil pollen and beetle assemblages are also close to this 4-5°C figure (McGlone, 2002; Sandiford et al., 2003; Wilmshurst et al., 2007).

There are problems with comparing paleotemperatures derived from different proxy sources because of issues of seasonality and sensitivity of the proxy indicators to climate variation. Our glaciological reconstructions present summer temperatures (DJF), which in cool climate periods are depressed less than winter temperatures. Thus, the glaciological method will underestimate the annual temperature depression at LGM. Hence, a key unresolved question is whether LGM mean annual temperature (MAT) estimates from other proxies serve as useful comparisons with reconstructed glacier ELA-based summer temperatures. Mountain glaciers in New Zealand appear to be most sensitive to summer temperatures (Anderson and Mackintosh, 2012), so that reconstructed ELAs based on summer temperature changes may at least be a first approximation on temperature changes during the LGM.

A second valid question is to what extent do empirical regressions derived from modern glaciers across the Northern Hemisphere form a basis for paleoglaciological reconstruction in New Zealand. Our Aston glacier reconstruction rests on the validity of Carr et al.'s (2010) regressions of summer temperature, annual precipitation, and ablation gradient. These are, in turn, based on Ohmura et al.'s (1992) compilation of data from 70 modern glaciers between latitudes 83°N and 66°S, of which 42 lie between 40°N and 65°N, and three are from the Southern Hemisphere. The

only New Zealand glacier in the compilation (Tasman Glacier) plots very close to Ohmura et al.'s (1992) regression line. Thus, the empirical basis for the range of ELA climates is strong because it covers almost the full global range of temperature, precipitation and radiation values.

A third issue concerns the variability within the dataset, which defines the probability that the reconstruction of any single glacier matches the global regression line. The standard deviation of the correlation between summer temperature and annual precipitation (Ohmura et al., 1992 Figure 2) defines a 68% probability that, for a given temperature, any glacier will lie between $\pm c.$ 450 mm of the mean annual accumulation value. This equates to $\pm c.$ 13% for a summer temperature of $+8^{\circ}\text{C}$, $\pm c.$ 23% for $+4^{\circ}\text{C}$, and $\pm c.$ 69% for 0°C . Thus, the temperature/precipitation relation is much better constrained for maritime glaciers like those in the Tararua Range than for continental glaciers. Glaciers in the Tararua Range at LGM had ELA summer temperatures $>3.2^{\circ}$ and $>3.7^{\circ}\text{C}$, therefore their paleoclimatic reconstruction will be towards the favourable maritime end of the spectrum where variability is relatively low, because both temperature and precipitation values are high.

Finally, uncertainty in the climatic reconstruction derives from (1) interpretation of glacier dimensions from fragmentary landforms; (2) statistical uncertainty (see above); and (3) local glaciological factors such as enhanced accumulation, aspect, and valley-side shading. Thus the derived climate envelope in which the Tararua Range glaciers existed is indicative rather than precise, because it is derived from generalised global relationships and involves a degree of glaciological simplification. Reconstructed paleoclimate is, however, insensitive to modest changes in glacier hypsometry which might occur with different extrapolations of glacier margins from limited landform evidence. More significant is the lack of precise information on snow accumulation patterns, local energy balance effects on ablation gradient, and so on. In spite of the necessary assumptions which must be made to cover these issues, glaciers are relatively simple physical systems in that they are controlled by a small number of primary climatic variables, and exist within known climatic constraints.

6. Conclusions

1. The limited development of glacier ice during the LGM in the Tararua Range compared with more extensive glaciation in the New Zealand Southern Alps, testifies to the steep temperature and precipitation gradients that existed over New Zealand. It appears that the Aston cirque glacier was only able to develop in a very favourable topoclimatic location in the southern Tararua Range below 1300 m a.s.l. ridgelines: a south-east facing basin, with a broad upper section which allowed snow to accumulate above the paleo-ELA. The moderate level of glacial erosion is indicative of a 'grade 4' cirque on the basis of the Evans and Cox (1995) cirque classification scheme. Further north in the Tararua Range, glaciation in valley heads beneath 1500 m a.s.l. ridgelines was more extensive, but still very limited compared to the Southern Alps and central North Island volcanoes. Nevertheless, classic landforms of glaciation are evident in Park Valley, including 'grade 1' cirques according to the Evans and Cox (1995) classification scheme, a lateral moraine, and U-shaped valley floor. Age controls on the Park Valley glacial geology indicates the valley has been glaciated at least twice in the late Quaternary.
2. During the LGM, the local equilibrium line altitude at the Aston cirque was *c.* 1290 m a.s.l, and this closely corresponds to the Park Valley paleo-ELA further north. This equates to a temperature depression of no greater than 5.5°C. This amount of cooling corresponds with other proxy temperature reconstructions from the LGM (e.g., McGlone, 2002), as well as typical temperature depressions based on Southern Alps glaciological reconstructions, and is consistent with the 5.6°C LGM temperature reduction reported by Eaves et al. (2016a) for Tongariro glaciers.
3. The reconstructions of Aston and Park Valley glaciers using Carr et al.'s (2010) method show that it is not always necessary to have an independent measure of either summer temperature or annual accumulation to constrain paleoclimate. The Aston glacier was so

marginally viable in terms of accumulation, that iterative application of a range of paleotemperature depression values identifies a threshold below which the glacier “dried up”: that is, the calculated balance flux was insufficient to support the annual mass gains and losses.

Acknowledgements

We thank John Rhodes for his long-term enthusiasm for this project, along with discussions over the years about the Aston basin, and other formerly glaciated sites in the Tararua Range. The efforts of two anonymous reviewers significantly improved the manuscript.

References

- Adkin, G.L., 1911. The discovery and extent of former glaciation in the Tararua Ranges, North Island, New Zealand. *Transactions of the New Zealand Institute* 44, 308–316.
- Alloway, B.V., Lowe, D.J., Barrell, D.J.A., Newnham, R.M., Almond, P.C., Augustinus, P.C., Bertler, N.A., Carter, L., Litchfield, N.J., McGlone, M.S., Shulmeister, J., Vandergoes, M.J., Williams, P.W. and NZ-INTIMATE members. 2007. Towards a climate event stratigraphy for New Zealand over the past 30 000 years (NZ-INTIMATE project). *Journal of Quaternary Science* 22(1), 9-35.
- Anderson, B., Mackintosh, A., 2012. Controls on mass balance sensitivity of maritime glaciers in the Southern Alps, New Zealand: the role of debris cover. *Journal of Geophysical Research - Earth Surface* 117, F01003.
- Anderson, B., Mackintosh, A., Stumm, D., George, L., Kerr, T., Winter-Billington, A., Fitzsimons, S., 2010. Climate sensitivity of a high-precipitation glacier in New Zealand. *Journal of Glaciology* 56(195), 114-128.
- Augustinus, P., 2002. Periglacial research in New Zealand: a review. *South African Journal of Science* 98(1-2), 64-70.
- Bacon, S.N., Chinn, T.J., Van Dissen, R.J., Tillinghast, S.F., Goldstein, H.L., Burke, R.M. 2001. Paleo-equilibrium line altitude estimates from late Quaternary glacial features in the Inland Kaikoura Range, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 44(1), 55-67.
- Barr, I.D., Spagnolo, M., 2015. Glacial cirques as palaeoenvironmental indicators: Their potential and limitations. *Earth-Science Reviews* 151, 48-78.
- Barrell, D.J.A., Almond, P.C., Vandergoes, M.J., Lowe, D.J., Newnham, R.M., 2013. A composite pollen-based stratotype for inter-regional evaluation of climatic events in New Zealand over the past 30,000 years (NZ-INTIMATE project). *Quaternary Science Reviews* 74, 4-20.
- Begg, J.G., Johnston, M.R., 2000. *Geology of the Wellington area: scale 1:250,000*. Institute of Geological & Nuclear Sciences, Lower Hutt.
- Benn, D.I., Ballantyne, C.K., 2005. Palaeoclimatic reconstruction from Loch Lomond re-advance glaciers in the West Drumochter Hills, Scotland. *Journal of Quaternary Science* 20, 577-592.
- Benn, D.I., Evans, D.J.A., 2010. *Glaciers and Glaciation*. Hodder Education, London. 802pp.
- Brook, M.S., 2009. Lateral moraine age in Park Valley, Tararua Range, New Zealand. *Journal of the Royal Society of New Zealand* 39(2-3), 63-69.
- Brook, M.S., Brock, B.W., 2005. Valley morphology and glaciation in the Tararua Range, southern North Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 48(4), 717-724.

- Brook, M.S., Crow, T.V.H., 2008. A debris ridge in Park Valley, Tararua Range, New Zealand, as evidence for Quaternary glaciation. *New Zealand Journal of Geology and Geophysics* 51(1), 23-28.
- Brook, M.S., Williams, J., 2012. A relict pronival (protalus) rampart in the Tararua Range, North Island, New Zealand. *Permafrost and Periglacial Processes* 24, 67-74.
- Brook, M.S., Purdie, H.L., Crow, T.V.H., 2005. Valley cross-profile morphology and glaciation in Park Valley, Tararua Range, New Zealand. *Journal of the Royal Society of New Zealand* 35(4), 399-407.
- Brook, M.S., Shulmeister, J., Crow, T.V.H., Zondervan, A., 2008. First cosmogenic Be-10 constraints on LGM glaciation on New Zealand's North Island: Park Valley, Tararua Range. *Journal of Quaternary Science* 23(8), 707-712.
- Brook, M.S., Neall, V.E., Stewart, R.B., Dykes, R.C., Birks, D.L., 2011. Recognition and paleoclimatic implications of late-Holocene glaciation on Mt Taranaki, North Island, New Zealand. *Holocene* 21(7), 1151-1158.
- Carr, S., Coleman, C., 2007. An improved technique for the reconstruction of former glacier mass-balance and dynamics. *Geomorphology* 92(1-2), 76-90.
- Carr, S.J., Lukas, S., Mills, S.C., 2010. Glacier reconstruction and mass-balance modelling as a geomorphic and palaeoclimatic tool. *Earth Surface Processes and Landforms* 35(9), 1103-1115.
- Chappell, P.R., 2014. The climate and weather of Wellington. NIWA Science and Technology Series Number 65. NIWA, Wellington.
- Cotton, C.A., Te Punga, M.T., 1955. Solifluxion and periglacially modified landforms at Wellington, New Zealand, *Transactions of the Royal Society of New Zealand* 82, 1001-1031.
- Darvill, C.M., Bentley, M.J., Stokes, C.R., Shulmeister, J., 2016. The timing and cause of glacial advances in the southern mid-latitudes during the last glacial cycle based on a synthesis of exposure ages from Patagonia and New Zealand. *Quaternary Science Reviews* 149, 200-214.
- Donoghue, S.L., Neall, V.E., Palmer, A.S., Stewart, R.B., 1997. The volcanic history of Ruapehu during the past 2 millennia based on the record of Tufa Trig tephra. *Bulletin of Volcanology* 59(2), 136-146.
- Doughty, A.M., Anderson, B.M., Mackintosh, A.N., Kaplan, M.R., Vandergoes, M.J., Barrell, D.J.A., Denton, G.H., Schaefer, J.M., Chinn, T.J.H., Putnam, A.E., 2013. Evaluation of Lateglacial temperatures in the Southern Alps of New Zealand based on glacier modelling at Irishman Stream, Ben Ohau Range. *Quaternary Science Reviews* 74, 160-169.

- Doughty, A.M., Schaefer, J.M., Putnam, A.E., Denton, G.H., Kaplan, M.R., Barrell, D.J.A., Andersen, B.G., Kelley, S.E., Finkel, R.C., Schwartz, R., 2015. Mismatch of glacier extent and summer insolation in Southern Hemisphere mid-latitudes. *Geology* 43(5), 407-410.
- Drost, F., Renwick, J., Bhaskaran, B., Oliver, H., McGregor, J., 2007. A simulation of New Zealand's climate during the Last Glacial Maximum. *Quaternary Science Reviews* 26, 2505-2525.
- Eaves, S.R., Mackintosh, A.N., Winckler, G., Schaefer, J.M., Alloway, B.V., Townsend, D.B., 2016a. A cosmogenic He-3 chronology of late Quaternary glacier fluctuations in North Island, New Zealand (39 degrees S). *Quaternary Science Reviews* 132, 40-56.
- Eaves, S.R., Mackintosh, A.N., Anderson, B.M., Doughty, A.M., Townsend, D.B., Conway, C., Winckler, G., Schaefer, J.M., Leonard, G.S., Calvert, A.T., 2016b. The Last Glacial Maximum in the central North Island, New Zealand: palaeoclimate inferences from glacier modelling. *Climate of the Past* 12(4), 943-960.
- Evans, I S., Cox, N.J., 1995. The form of glacial cirques in the English Lake District, Cumbria. *Zeitschrift Fur Geomorphologie* 39(2), 175-202.
- Finlayson, A.G., Golledge, N., Bradwell, T., Fabel, D., 2011. Evolution of a Lateglacial mountain icecap innorthern Scotland. *Boreas* 40, 536-554.
- Golledge, N.R., Mackintosh, A.N., Anderson, B.M., Buckley, K.M., Doughty, A.M., Barrell, D.J.A., Denton, G.H., Vandergoes, M.J., Andersen, B.G., Schaefer, J.M., 2012. Last Glacial Maximum climate in New Zealand inferred from a modelled Southern Alps icefield. *Quaternary Science Reviews* 46, 30-45.
- Harrison, S., Knight, J., Rowan, A.V., 2015. The southernmost Quaternary niche glacier system in Great Britain. *Journal of Quaternary Science* 30(4), 325-334.
- Kirkbride, M.P., Everest, J., Benn, D., Gheorghiu, D. and Dawson, A., 2014. Late-Holocene and Younger Dryas glaciers in the northern Cairngorm Mountains, Scotland. *The Holocene* 24, 141-148.
- Kirkbride, M.P., Mitchell, W.A., Barnes, M., 2015. Reconstruction and Regional Significance of the Coire Breac Palaeoglacier, Glen Esk, Eastern Grampian Highlands, Scotland. *Geografiska Annaler Series A-Physical Geography* 97(3), 563-577.
- Lamont, G.N., Chinn, T.J., Fitzharris, B.B., 1999. Slopes of glacier ELAs in the Southern Alps of New Zealand in relation to atmospheric circulation patterns. *Global and Planetary Change* 22(1-4), 209-219.
- Mathews, W.H., 1967. Profiles of late Quaternary glaciers in New Zealand. *New Zealand Journal of Geology and Geophysics* 10(1), 146-163.

- McArthur, J.L., Shepherd, M.J., 1990. Late Quaternary glaciation of Mt Ruapehu, North Island, New Zealand. *Journal of the Royal Society of New Zealand* 20(3), 287-296.
- McGlone, M., 2002. A Holocene and latest Pleistocene pollen record from Lake Poukawa, Hawke's Bay, New Zealand. *Global and Planetary Change* 33, 283-299.
- McGlone, M.S., Topping, W.W., 1983. Late Quaternary vegetation, Tongariroregion, central North Island, New Zealand. *New Zealand Journal of Botany* 21, 53-76.
- McKinnon, K.A., Mackintosh, A.N., Anderson, B.M., Barrell, D.J.A., 2012. The influence of sub-glacial bed evolution on ice extent: a model-based evaluation of the Last Glacial Maximum Pukaki glacier, New Zealand. *Quaternary Science Reviews* 57, 46-57.
- McLea, W.L., 1990. Palynology of Pohehe Swamp, northwest Wairarapa, New Zealand: a study of climatic and vegetation changes during the last 41 000 years. *Journal of the Royal Society of New Zealand* 20, 205-220.
- Mitchell, W.A., 1996. Significance of snow blow in the generation of Loch Lomond Stadial (Younger dryas) glaciers in the western Pennines, northern England. *Journal of Quaternary Science* 11(3), 233-248.
- Nesje A, Dahl SV. (2000). *Glaciers and environmental change*. Arnold, London. 203pp
- Nicol, A., Beavan, J., 2003. Shortening of an overriding plate and its implications for slip on a subduction thrust, central Hikurangi Margin, New Zealand. *Tectonics*, 22(6)
10.1029/2003tc001521
- Ohmura, A., Kasser, P., Funk, M., 1992. Climate at the equilibrium line of glaciers. *Journal of Glaciology* 38(130), 397-411.
- Pahnke, K., Sachs, J.P., 2006. Sea surface temperatures of southern mid latitudes 0-160 kyr BP. *Paleoceanography* 21, PA2003
- Plummer, M.A., Phillips, F.M., 2003. A 2-D numerical model of snow/ice energy balance and ice flow for paleoclimatic interpretation of glacial geomorphic features. *Quaternary Science Reviews* 22(14), 1389-1406.
- Porter, S.C., 1975. Equilibrium-line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. *Quaternary Research* 5(1), 27-47.
- Purdie, H., Anderson, B., Chinn, T., Owens, I., Mackintosh, A., Lawson, W., 2014. Franz Josef and Fox Glaciers, New Zealand: Historic length records. *Global and Planetary Change* 121, 41-52.
- Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Birkel, S.D., Andersen, B.G., Kaplan, M.R., Finkel, R.C., Schwartz, R., Doughty, A.M., 2013. The Last Glacial Maximum at 44 degrees S documented by a Be-10 moraine chronology at Lake Ohau, Southern Alps of New Zealand. *Quaternary Science Reviews* 62, 114-141.

- Sandiford, A., Newnham, R., Alloway, B., Ogden, J., 2003. A 28000–7600 cal yr BP pollen record of vegetation and climate change from Pukaki Crater, northern New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* 201, 235–247.
- Seltzer, A., Stute, M., Morgenstern, U., Stewart, M., Schaefer, J., 2015. Mean annual temperature in new zealand during the last glacial maximum derived from dissolved noble gases in groundwater. *Earth and Planetary Science Letters* 431, 206–216.
- Shulmeister, J., Shane, P., Lian, O.B., Okuda, M., Carter, J.A., Harper, M., Dickinson, W., Augustinus, P., Heijnis, H., 2001. A long late-Quaternary record from Lake Poukawa, Hawke's Bay, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology* 176, 81–107.
- Shulmeister, J., Goodwin, I., Renwick, J., Harle, K., Armand, L., McGlone, M.S., Cook, E., Dodson, J., Hesse, P.P., Mayewski, P., Curran, M., 2004. The Southern Hemisphere westerlies in the Australasian sector over the last glacial cycle: a synthesis. *Quaternary International* 118, 23–53.
- Shulmeister, J., Fink, D., Hyatt, O.M., Thackray, G.D., Rother, H., 2010. Cosmogenic Be-10 and Al-26 exposure ages of moraines in the Rakaia Valley, New Zealand and the nature of the last termination in New Zealand glacial systems. *Earth and Planetary Science Letters* 297(3–4), 558–566.
- Sissons, J.B., 1980. The Loch Lomond Advance in the Lake District, northern England. *Transactions of the Royal Society of Edinburgh (Earth Sciences)* 71, 13–27.
- Stratford, W.R., Stern, T.A., 2006. Crust and upper mantle structure of a continental backarc: central North Island, New Zealand. *Geophysical Journal International* 166(1), 469–484.
- Weertman, J., 1971. Shear stress at the base of a rigidly rotating cirque glacier. *Journal of Glaciology* 10(58), 31–37.
- Whittaker, T.E., Hendy, C.H., Hellstrom, J.C., 2011. Abrupt millennial-scale changes in intensity of Southern Hemisphere westerly winds during marine isotope stages 2–4. *Geology* 39, 455–458.
- Wilmshurst, J.M., McGlone, M.S., Leathwick, J.R., Newnham, R.M., 2007. A pre-deforestation pollen-climate calibration model for New Zealand and quantitative temperature reconstructions for the past 18000 years BP. *Journal of Quaternary Science* 22, 535–547.

Table 1: Reconstructed steady-state glaciological parameters for the Aston cirque glacier and the Park Valley glacier (P_a , total accumulation at ELA; a_z , ablation gradient).

LGM JJA temp decrease °C	P_a mm ⁻¹ w.e	a_z mm m ⁻¹	Balance flux m ³ yr ⁻¹	u, balance velocity m yr ⁻¹	Creep velocity m yr ⁻¹	% basal sliding	Balance flux × 10 ³ m ³ yr ⁻¹
<i>Mt Aston cirque glacier</i>							
-1	3458	0.013	37129	2.48	1.07	56.9	37
-2	3032	0.00879	30501	2.04	1.07	47.5	31
-3	2625	0.00722	25053	1.68	1.07	36.3	25
-4	2235	0.00596	20681	1.38	1.07	22.5	21
-5	1863	0.00498	17281	1.16	1.07	7.8	17
-6	1510	0.00425	14748	0.99	1.07	-8.1	15
-7	1174	0.00374	12978	0.87	1.07	-23.0	13
-8	857	0.00342	11867	0.79	1.07	-35.4	12
-9	557	0.00326	11312	0.76	1.07	-40.8	11
<i>Park Valley glacier</i>							
-1	3677	0.0118	325385	23.67	0.73	96.7	325
-2	3243	0.0097	267302	19.44	0.73	96.2	267
-3	2826	0.00796	219559	15.97	0.73	95.4	220
-4	2428	0.00656	181243	13.18	0.73	94.5	181
-5	2047	0.00544	151441	11.02	0.73	93.4	151
-6	1684	0.00459	129242	9.40	0.73	92.2	129
-7	1340	0.00397	113733	8.27	0.73	91.2	114
-8	1013	0.00356	104002	7.56	0.73	90.3	104
-9	705	0.00332	99136	7.21	0.73	89.9	99

Table 2: Potential snow blow areas (in km²) and factors in the vicinity of the Aston cirque basin, by 90° sectors, following Mitchell (1996).

	Glacier area (km²)	Total snow blow area (km²)	NE (0-90°)	SE (91- 180°)	SW (181-270°)	NW (271-360°)	N (271- 90°)	E (0-180°)
Area (km ²)	0.132	2.63	2.14	0.09	0.27	0.13	2.28	2.23
Factor	0.132	19.95	11.09	2.30	3.93	2.73	11.42	11.57

Table 3: Potential snow blow areas (in km²) and factors in the vicinity of the Park Valley glacier, by 90° sectors, following Mitchell (1996).

	Glacier area (km²)	Total snow blow area (km²)	NE (0-90°)	SE (91- 180°)	SW (181-270°)	NW (271-360°)	N (271- 90°)	E (0-180°)
Area (km ²)	0.422	3.72	3.36	0.10	0.00	0.25	3.67	3.46
Factor	0.422	8.81	4.34	0.76	0.00	1.20	4.50	4.41

List of figure captions

Figure 1. Location map of the study site in the southern Tararua Range on the lower North Island of New Zealand. The position of the southeast-facing Aston cirque basin is shown in relation to the other established paleo-glacier sites, including Park Valley, as identified by Adkin (1911) and Brook and Brock (2005). The shaded relief map is from the Land Information New Zealand (LINZ) 8 m digital elevation model (DEM) of 2012 (<https://data.linz.govt.nz>).

Figure 2. Views of the Aston site location and geomorphology. (A) View northwest toward the backwall of the cirque basin with basin floor incised by tributary of Tauherenikau River. (B) View northeast across the cirque basin, with rounded side-slopes evident.

Figure 3. Geomorphological map of the Aston cirque basin. Dotted line indicates inferred glacier margin above the paleo-ELA.

Figure 4. Views of the Park Valley site location and geomorphology. (A) Eastern-most cirque-basin and lateral moraine used for the MELM-ELA method. (B) Western-most cirque basin, with smooth side-slopes and backwall. (C) View down-valley, showing the lateral moraine (arrowed). (D) View across-valley showing the lateral moraine and position (arrowed) used for the MELM-ELA.

Figure 5. Geomorphological map of the Park Valley cirque basins and lateral moraine. Dotted line indicates inferred glacier margin above the paleo-ELA.

Figure 6. Glacier hypsometry of the (A) Aston cirque glacier and (B) Park Valley glacier. Thick line = percentage of glacier area per 20 m altitude class; thin line = cumulative percentage area by altitude class. Horizontal and vertical lines indicate the ELA for three different values of AAR (0.5, 0.6, 0.7), where an AAR of 0.6 = 40% area below the ELA.

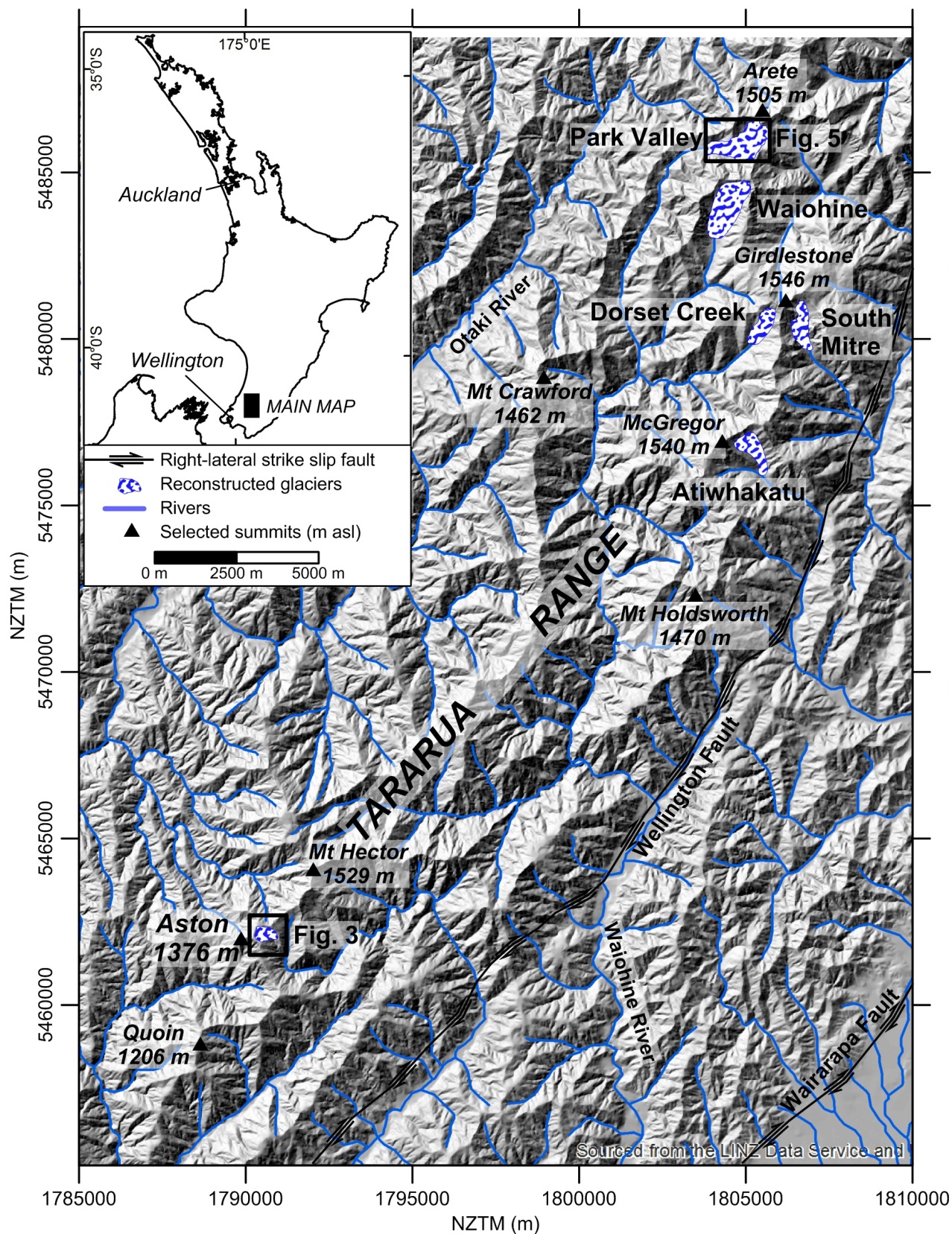
Figure 7. Glacier reconstruction of the Aston cirque (A-D) and Park Valley glacier (E-H), showing for each reconstruction: surface elevation (m), surface slope (degrees), ice thickness (m), basal shear stress (kPa). Reconstructions are based on the shapefile of 20 m contours from the Land Information New Zealand (LINZ) 8 m digital elevation model (DEM) of 2012 (<https://data.linz.govt.nz>).

Figure 8. Summer (DJF) freezing levels (m a.s.l.) from the 1967-1991 temp records from the five climate stations shown (data from NIWA Cliflo database).

Figure 9. Reconstructed mass balance flux ($\times 10^3 \text{ m}^3 \text{ yr}^{-1}$) and % sliding velocity for both the reconstructed Aston cirque glacier and the Park Valley glacier, for a range of LGM temperature depressions. Aston Glacier is unviable (shaded area) once the temperature depression exceeds -5.5°C . Also included on the plot are selected temperature depressions for New Zealand during the LGM.

Figure 10. (A) Potential snow blow area for the Aston cirque glacier, defined with respect to surfaces adjacent to the former glacier lying upslope of the ELA (e.g., Mitchell, 1996); N/I indicates areas that have not been included in the calculations. (B) Polar plot of the snow blow area and orientation by 15° sector. (C) Polar plot of snow blow factor and orientation by 15° sector.

Figure 11. (A) Potential snow blow area for the Park Valley glacier, defined with respect to surfaces adjacent to the former glacier lying upslope of the ELA (e.g., Mitchell, 1996); N/I indicates areas that have not been included in the calculations. (B) Polar plot of the snow blow area and orientation by 15° sector. (C) Polar plot of snow blow factor and orientation by 15° sector.

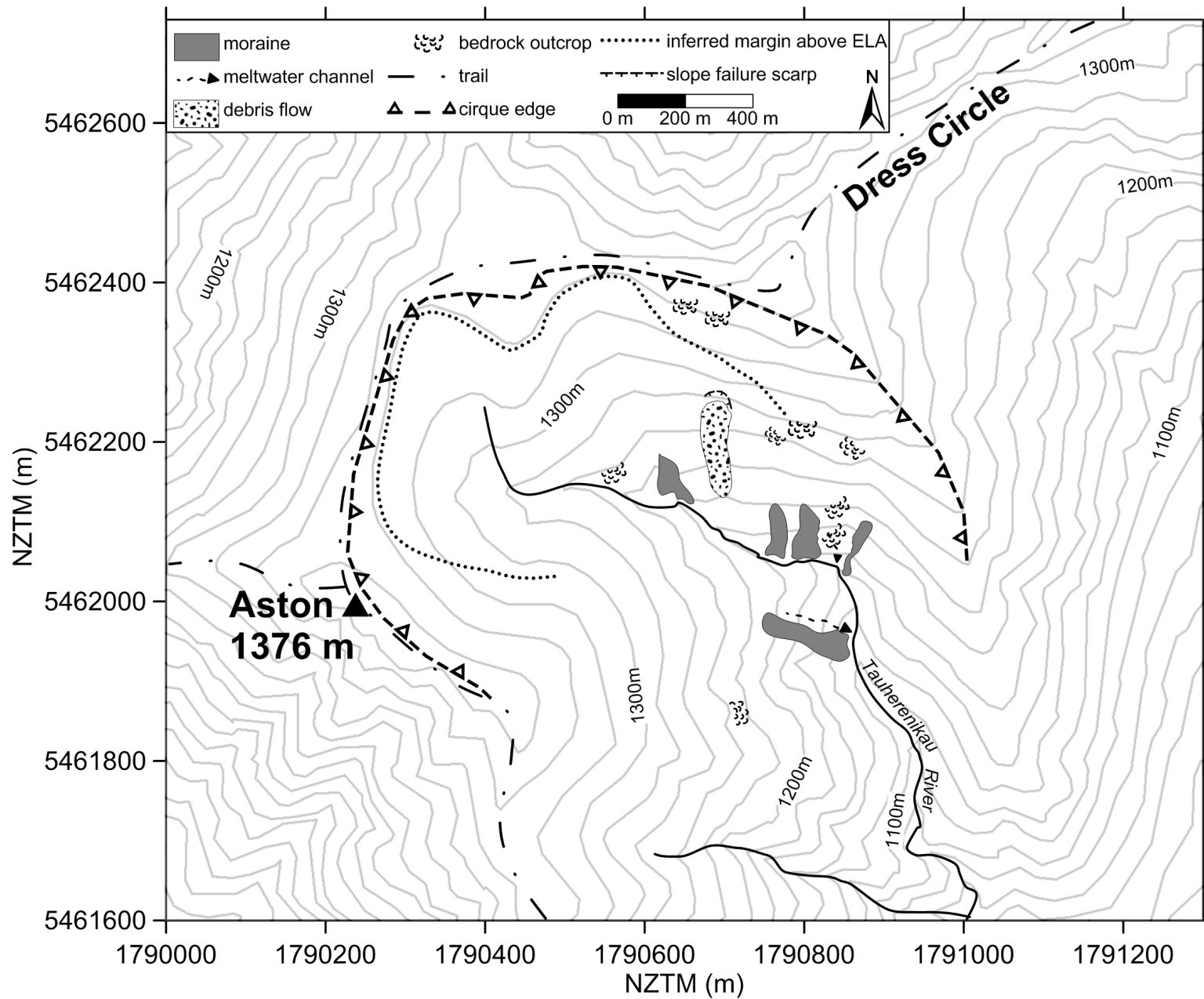


A

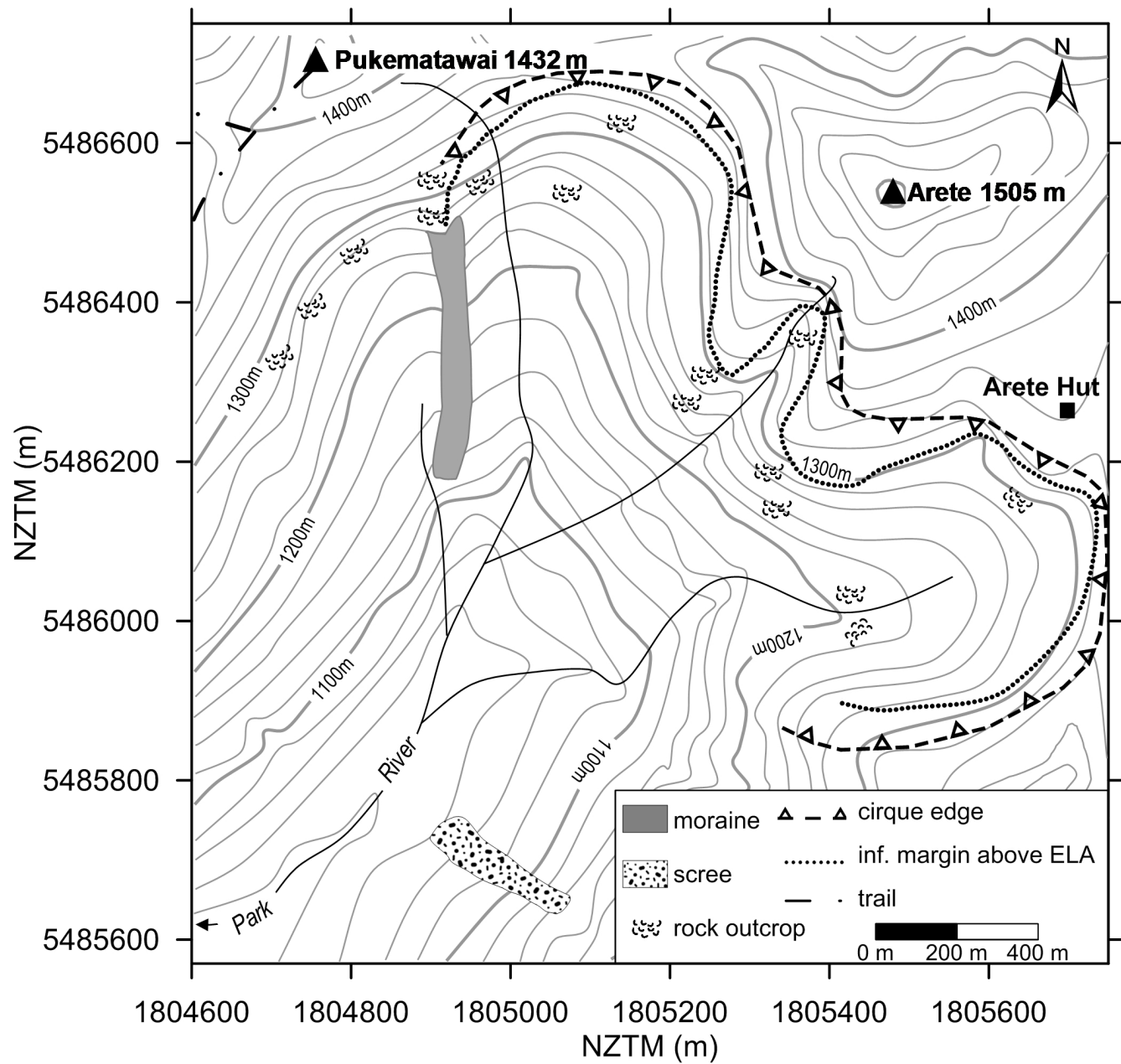


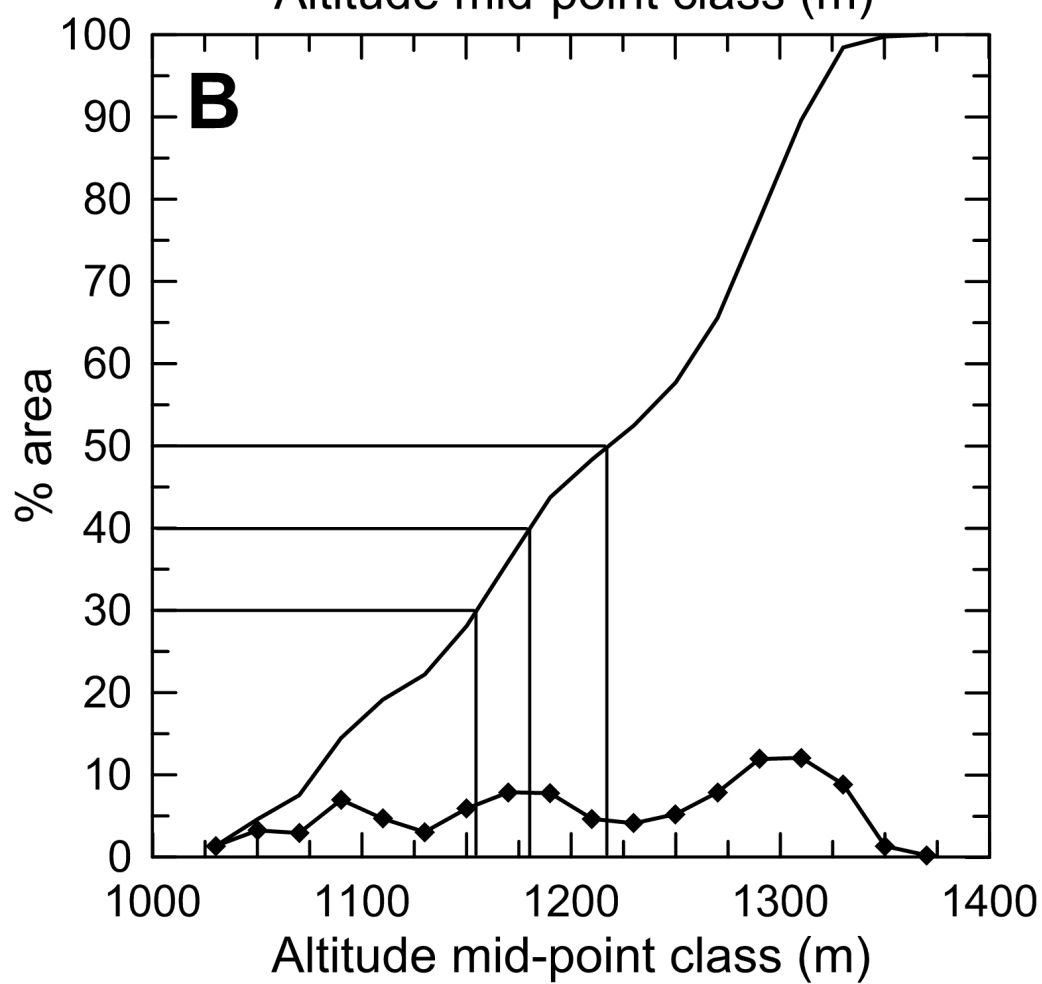
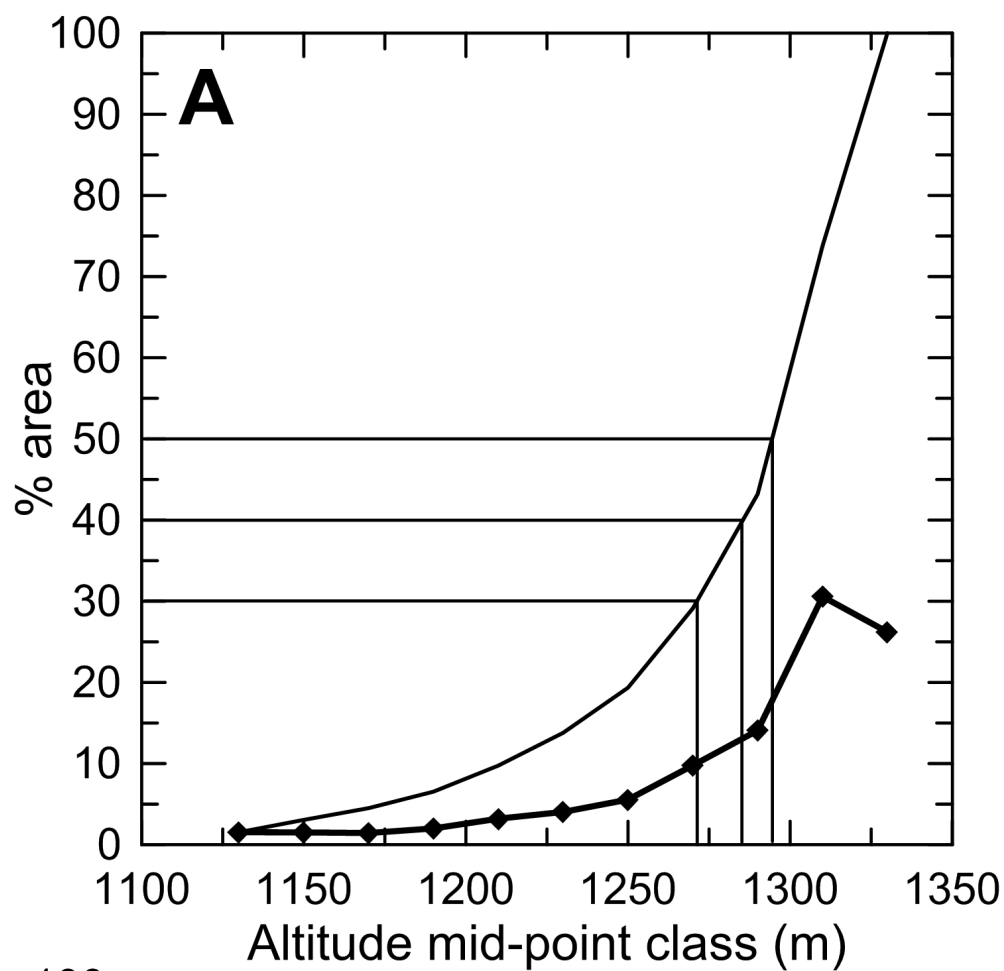
B

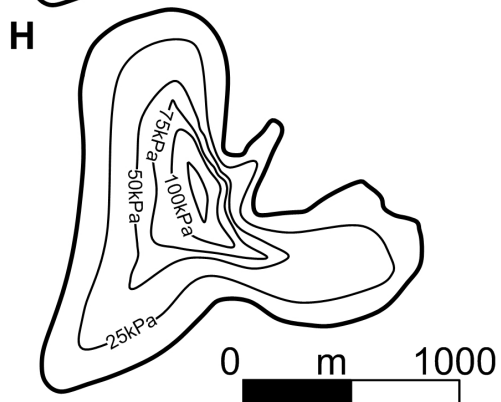
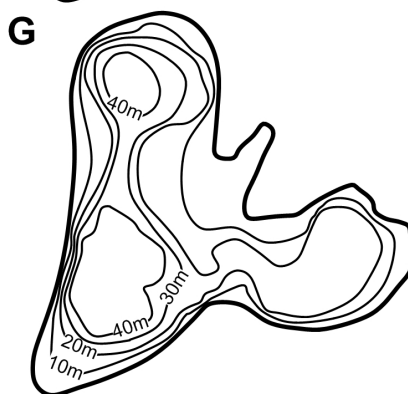
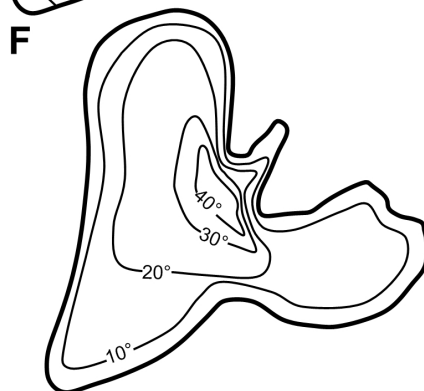
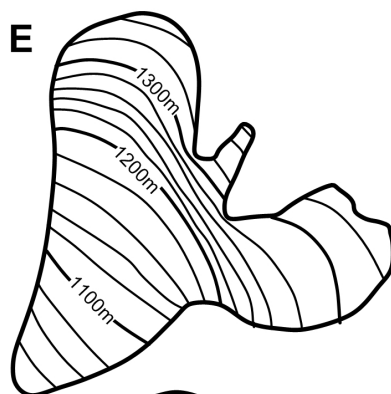
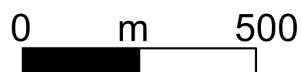
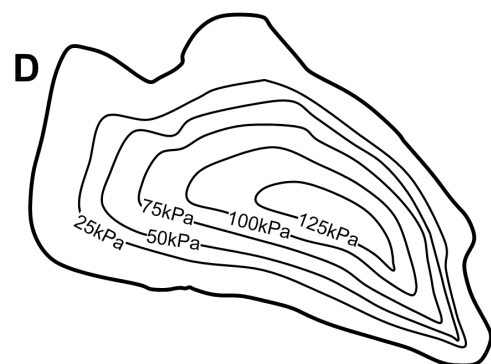
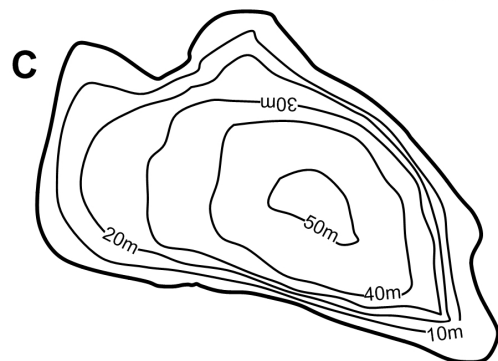
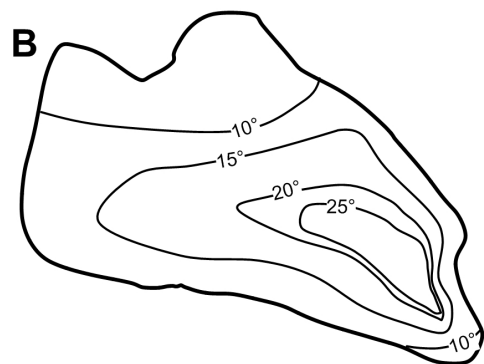
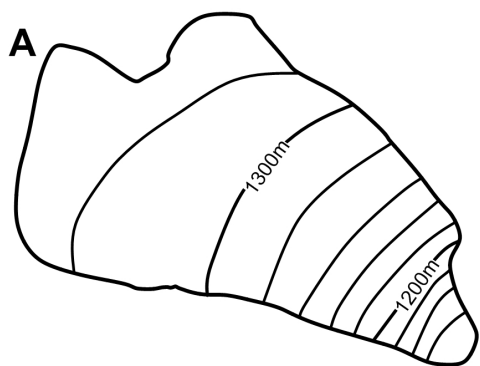


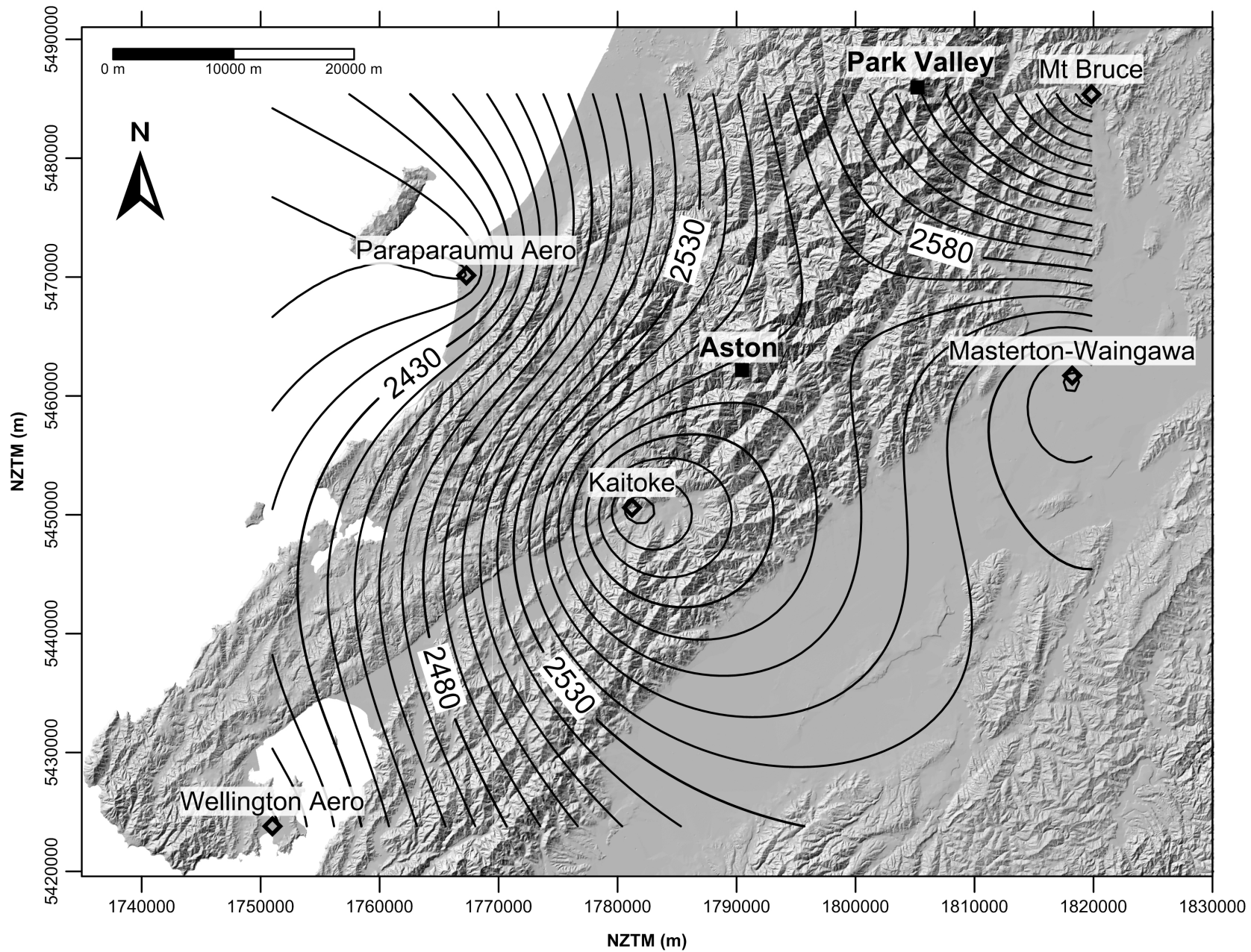


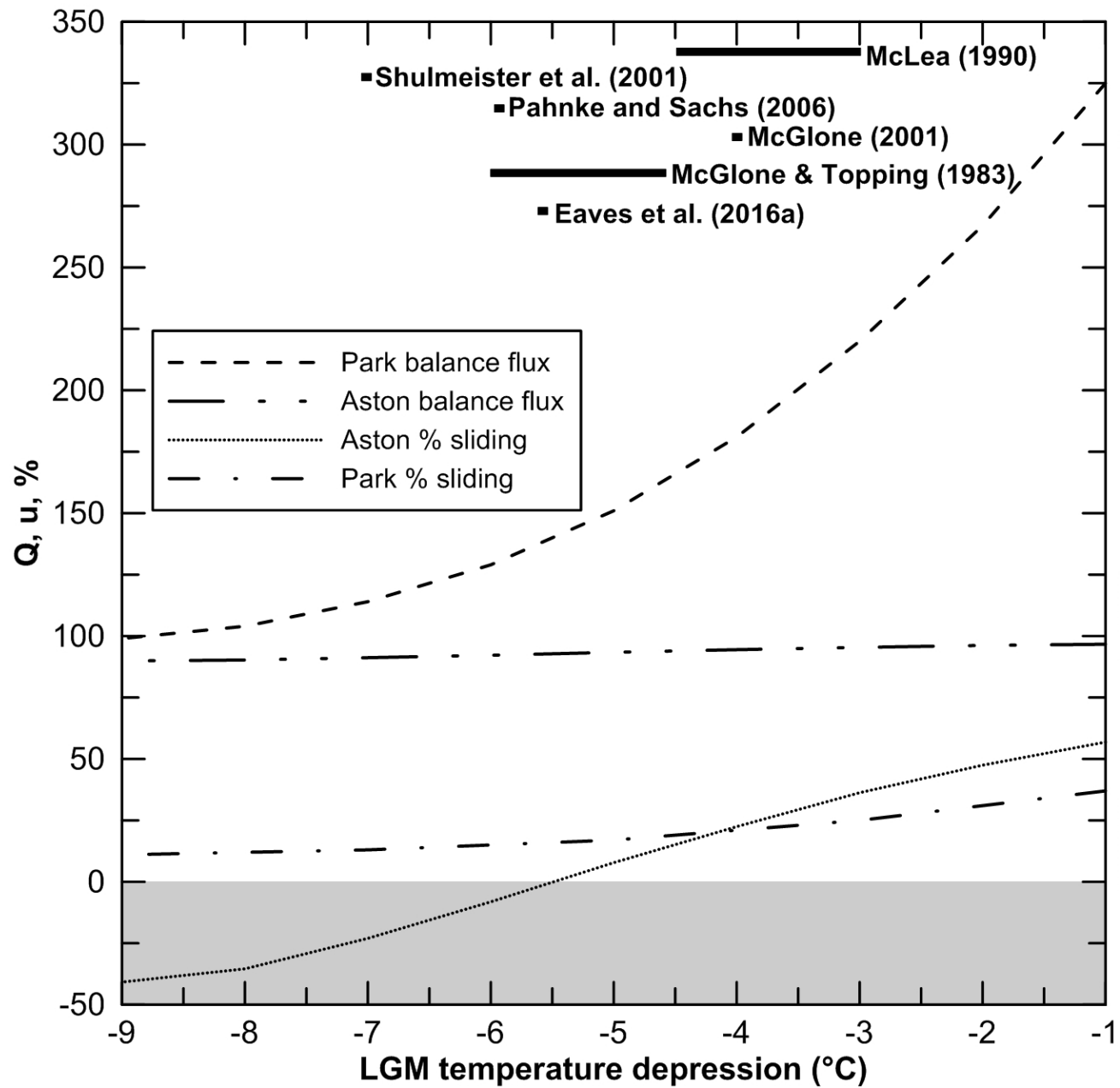


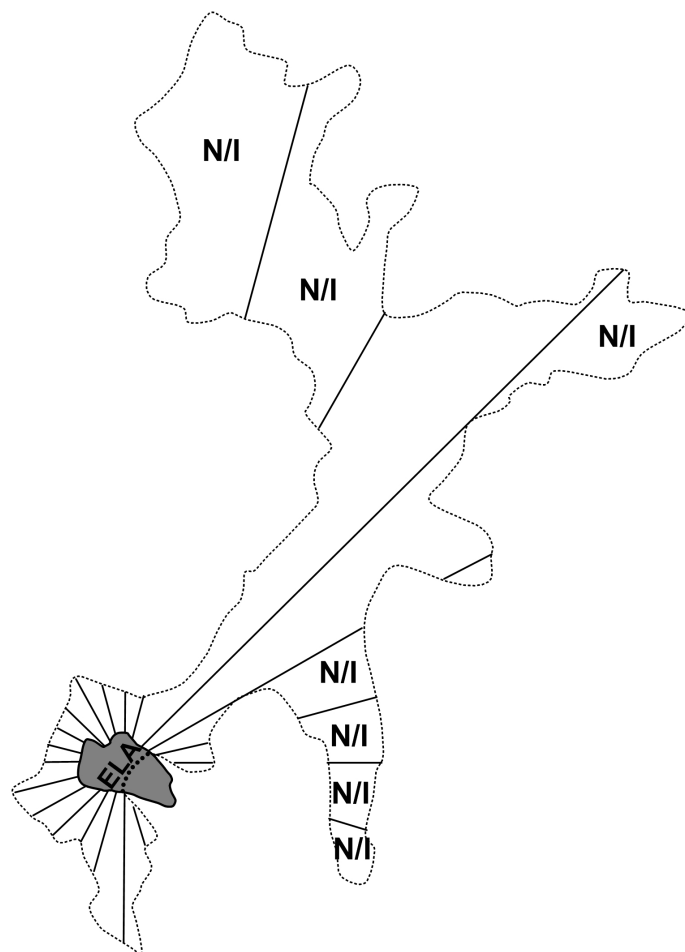
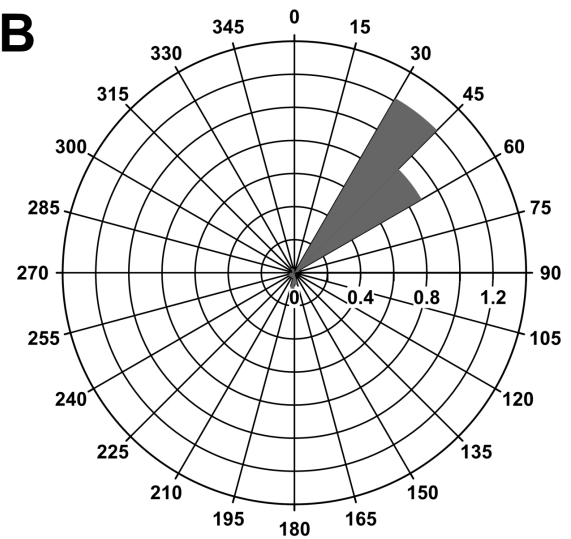
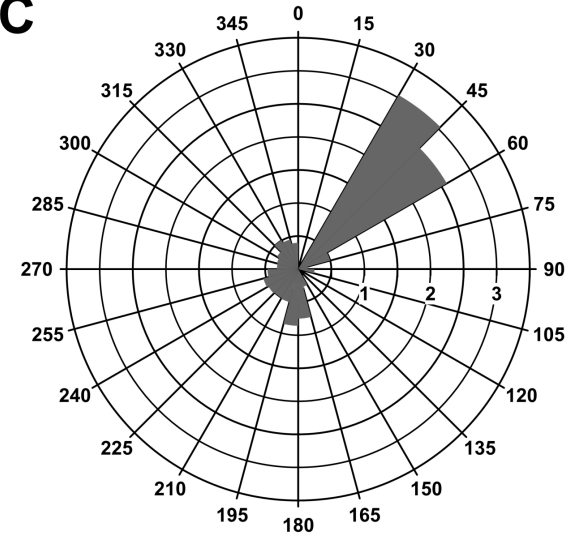


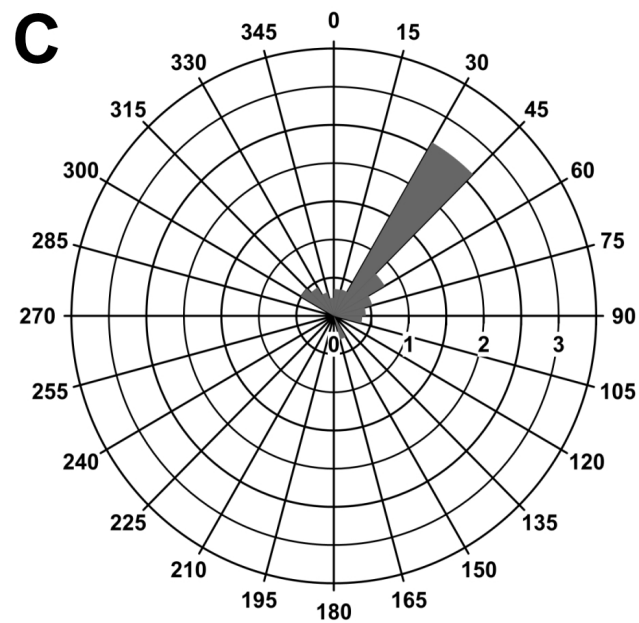
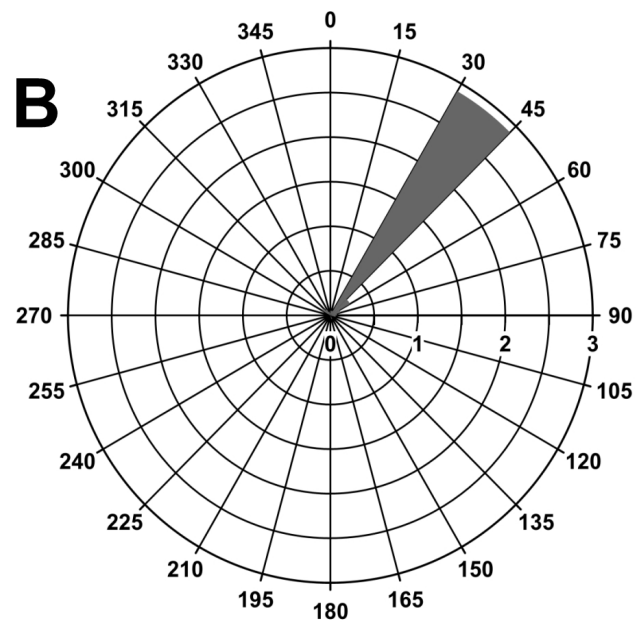
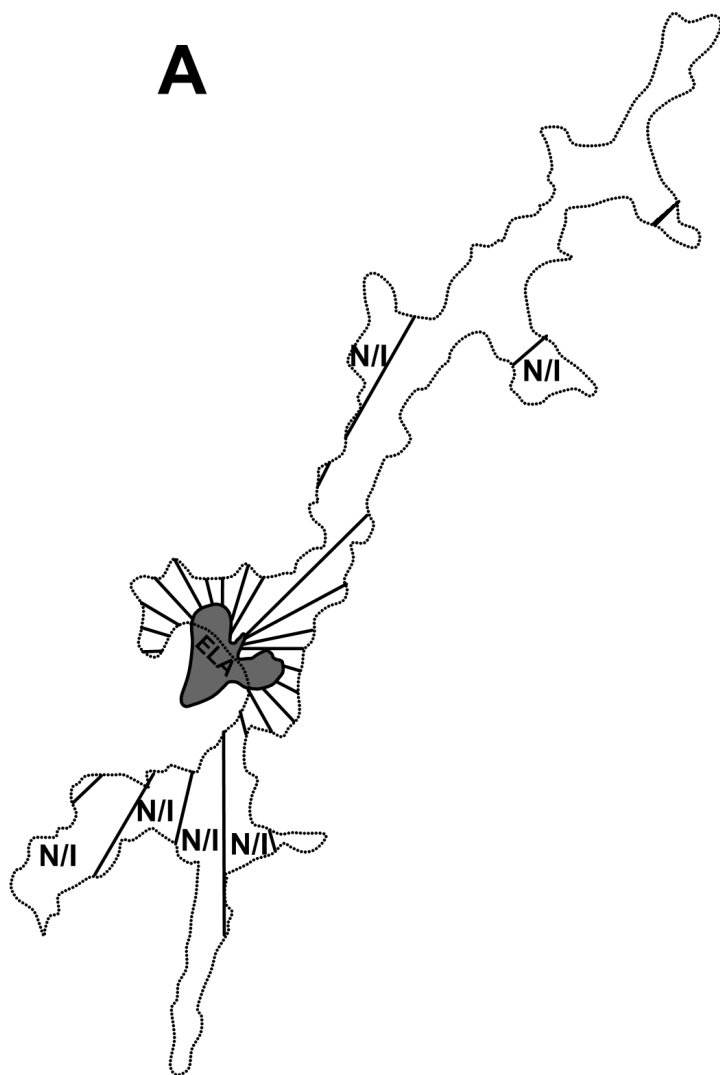








A**B****C**



Quaternary International

We the authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process. He/She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs.

Sincerely,
MARTIN BROOK
On behalf of all authors